Development of High Efficiency Segmented Thermoelectric Couples for Space Applications

Fivos Drymiotis[1], Jean-Pierre Fleurial [1], Sabah Bux [1], Samad Firdosy [1], Kurt Start [1], Ike Chi [1], Vilupanur Ravi [1,2], Billy Chun-Yip Li [1], Sevan Chanakian [3], Dean Cheikh [1], Kathy Lee[1], Kevin Yu [1], Obed Villalpando [13], Kevin Smith [1], David Uhl [1], Chen-Kuo Huang [1], Jong-Ah Paik [1], Knut Oxnevut [1], Zi-Kui Liu [4], Jorge Paz Soldan Palma [4], Yi Wang [4], XiaoYu Chong [4], Frances Hurwitz [5], Dongming Zhu [5], Haiquan Guo [5], Gustavo Costa [5].

[1]**Jet Propulsion Laboratory-California Institute of Technology, Pasadena CA 91109**
[2]California State Polytechnic University Pomona, Pomona CA 91768
[3]Michigan State University, East Lansing MI 48824,
[4]Penn State University, State College, PA 16801
[5]NASA Glenn Research Center, Cleveland, OH 44135

Historical RTG-Powered U.S. Missions

Mission	RTG type (number)	TE	Destination	Launch Year	Mission Length	Power Level*
Transit 4A	SNAP-3B7(1)	PbTe	Earth Orbit	1961	15	2.7
Transit 4B	SNAP-3B8 (1)	PbTe	Earth Orbit	1962	9	2.7
Nimbus 3	SNAP-19 RTG (2)	PbTe	Earth Orbit	1969	> 2.5	~ 56
Apollo 12[#]	SNAP-27 RTG (1)	PbTe	Lunar Surface	1969	8	~ 70
Pioneer 10	SNAP-19 RTG (4)	PbTe	Outer Planets	1972	34	~ 160
Triad-01-1X	SNAP-9A (1)	PbTe	Earth Orbit	1972	15	~ 35
Pioneer 11	SNAP-19 RTG (4)	PbTe	Outer Planets	1973	35	~ 160
Viking 1	SNAP-19 RTG (2)	PbTe	Mars Surface	1975	> 6	~ 84
Viking 2	SNAP-19 RTG (2)	PbTe	Mars Surface	1975	> 4	~ 84
LES 8	MHW-RTG (2)	Si-Ge	Earth Orbit	1976	15	~ 308
LES 9	MHW-RTG (2)	Si-Ge	Earth Orbit	1976	15	~ 308
Voyager 1	MHW-RTG (3)	Si-Ge	Outer Planets	1977	40	~475
Voyager 2	MHW-RTG (3)	Si-Ge	Outer Planets	1977	40	~475
Galileo	GPHS-RTG (2)	Si-Ge	Outer Planets	1989	14	~ 574
Ulysses	GPHS-RTG (1)	Si-Ge	Outer Planets/Sun	1990	18	~ 283
Cassini	GPHS-RTG (3)	Si-Ge	Outer Planets	1997	20	~ 885
New Horizons	GPHS-RTG (1)	Si-Ge	Outer Planets	2005	12 (17)	~ 246
MSL	MMRTG (1)	PbTe	Mars Surface	2011	6 (to date)	~ 115
*Mars 2020***	*MMRTG (1 baselined)*	*PbTe*	*Mars Surface*	*2020*	*(5)*	*> 110*

[#]Apollo 12, 14, 15, 16 and 17
**Planned

Total power at Beginning of Mission (W)

From a few watts up to ~ 900 W, up to 40 years of operation (and counting)

Request for the NG-RTG Study

Was motivated by the need for larger RTGs than presently available or near-term improvements

- **Serve NASA for 2-3 decades** to come
- To address the needs of future Decadal Survey missions

✓ An RTG that would be useful **across** the **Solar System**

✓ An RTG that **maximizes** the types of **missions**: flyby, orbit, land, rove, boats, submersibles, balloons

✓ An RTG that has **reasonable** development **risks** and **timeline**

"**OPAG** is in support of pursuing the advancement and maturation of segmented thermoelectric converter technology for development of a modular Next Generation RTG …" (La Jolla, 2017)

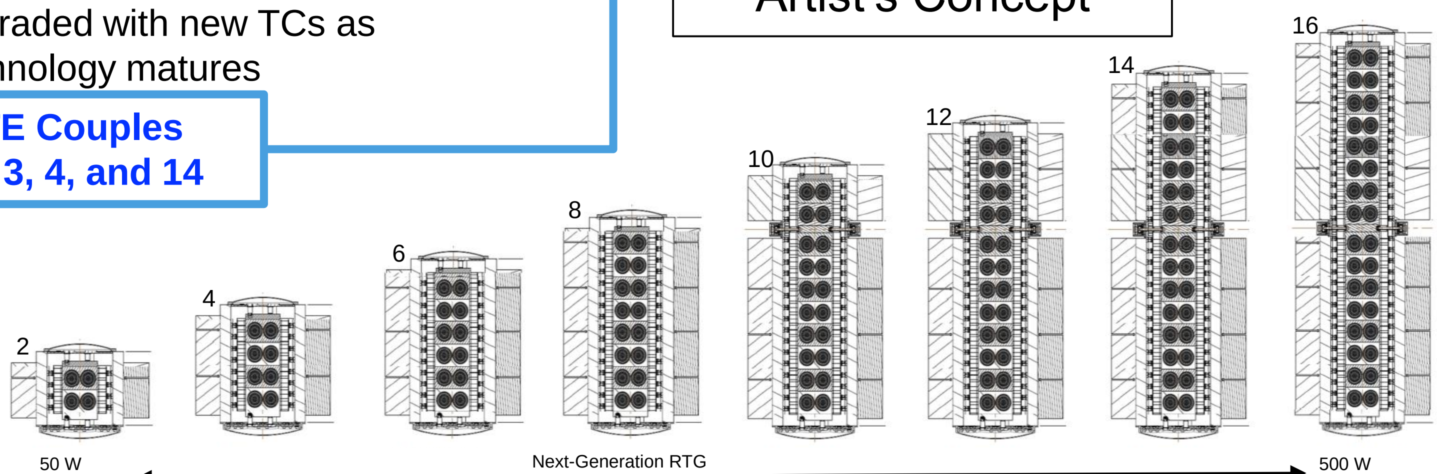
Recommendations

- **NG-RTG:**
  - Vacuum Only
  - Modular
- **Variants**: **2, 4, 6, 8, 10, 12, 14**, and **16 GPHS** variants
  - 16 GPHSs (largest RTG variant)
  - P_{BOM} = **400-500 W_e** (largest RTG variant)
  - Mass goal of < **60 kg** (largest RTG variant)
  - Degradation rate **< 1.9 %**
  - System to be designed to be upgraded with new TCs as technology matures

•Selected TE Couples
•1, 2, 3, 4, and 14

Configuration	n		p		~Couple Efficiency at T_{cj} = 450K	~ Generator Efficiency (16 GPHSs)
	Low	High	Low	High		
1	1-2-2 Zintl	$La_{3-x}Te_4$/composite	9-4-9 Zintl	14-1-11 Zintl	16.6	14.8
2	1-2-2 Zintl	$La_{3-x}Te_4$	9-4-9 Zintl	14-1-11 Zintl	15.3	13.6
3	SKD	$La_{3-x}Te_4$/composite	SKD	14-1-11 Zintl	15.7	13.9
4	SKD	$La_{3-x}Te_4$	SKD	14-1-11 Zintl	14.3	12.7
14		$La_{3-x}Te_4$/composite		14-1-11 Zintl	13.6	12.1

Artist's Concept



Technology Objective and Work Element Organization

Technology Objective:

- **Develop and demonstrate advanced thermoelectric couples capable of supporting the Next Generation RTGs with:**
  ≥ 11% system conversion efficiency
  (≥ 60% improvement over MMRTG at BOL)
  ≥ 6-8.5 We/kg specific power
  (2-3 x improvement over MMRTG)

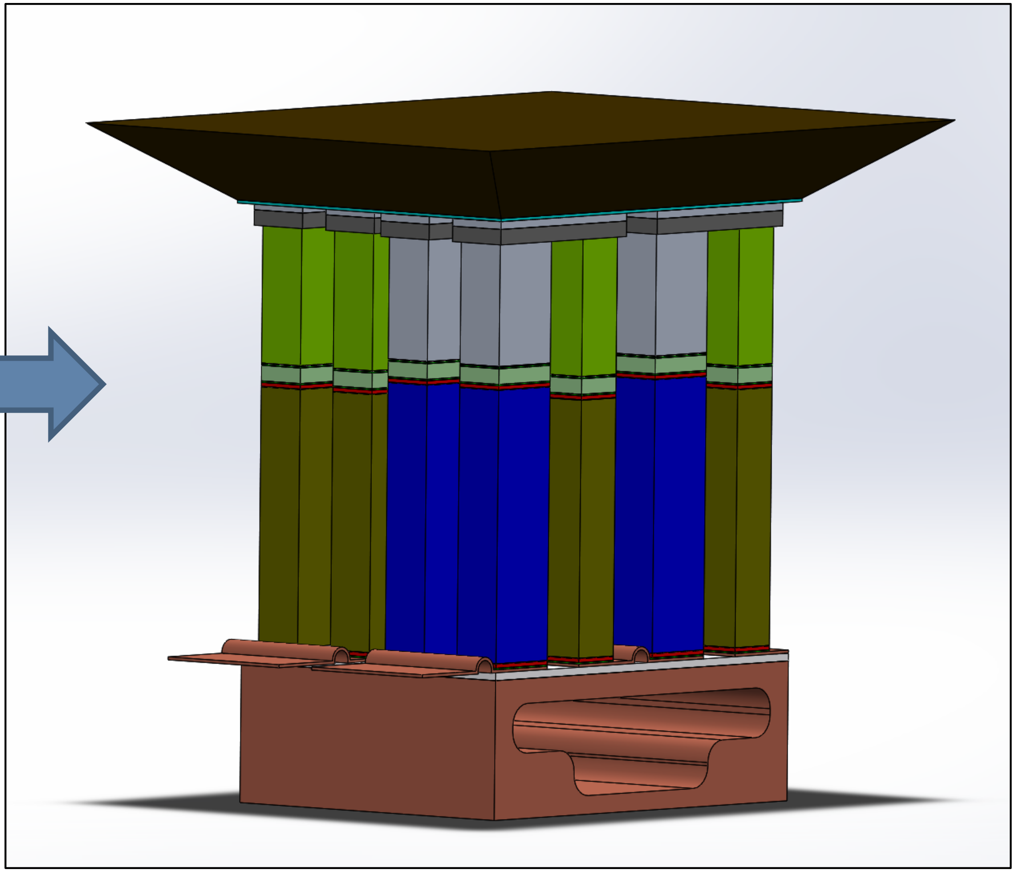
- **Prediction of 1.9%/year or lower power degradation average over 17 years (including isotope decay)**

- **Develop and maintain technology maturation plan for module development**

Work Element Organization

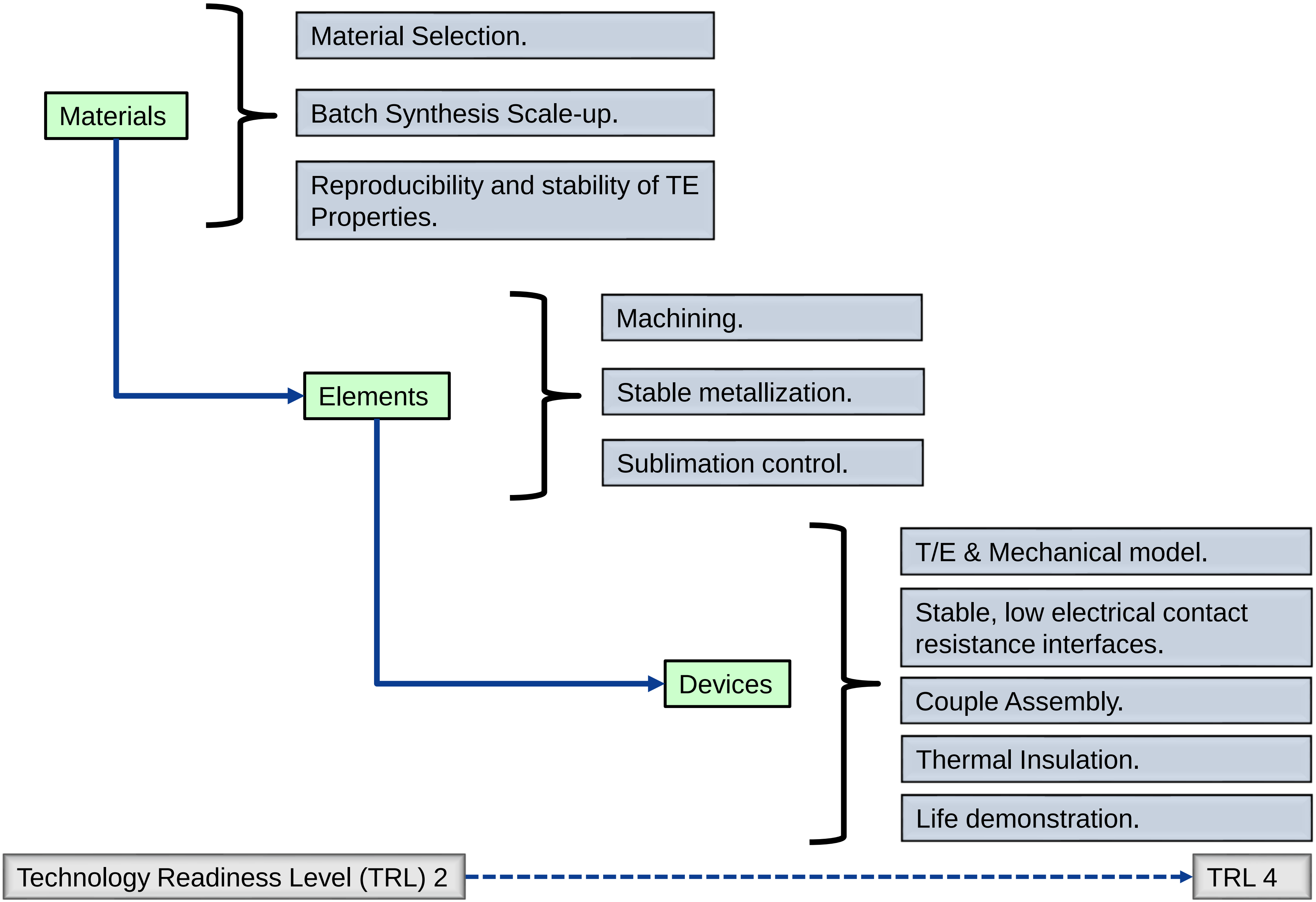
- Lead: Jet Propulsion Laboratory
- Collaborators: Glenn Research Center (GRC)
- Subcontractors: *ATA Engineering*, *University of Southern California (USC)*, University of Mississippi, Penn State University, *Harvard*

Technical Challenges Summarized

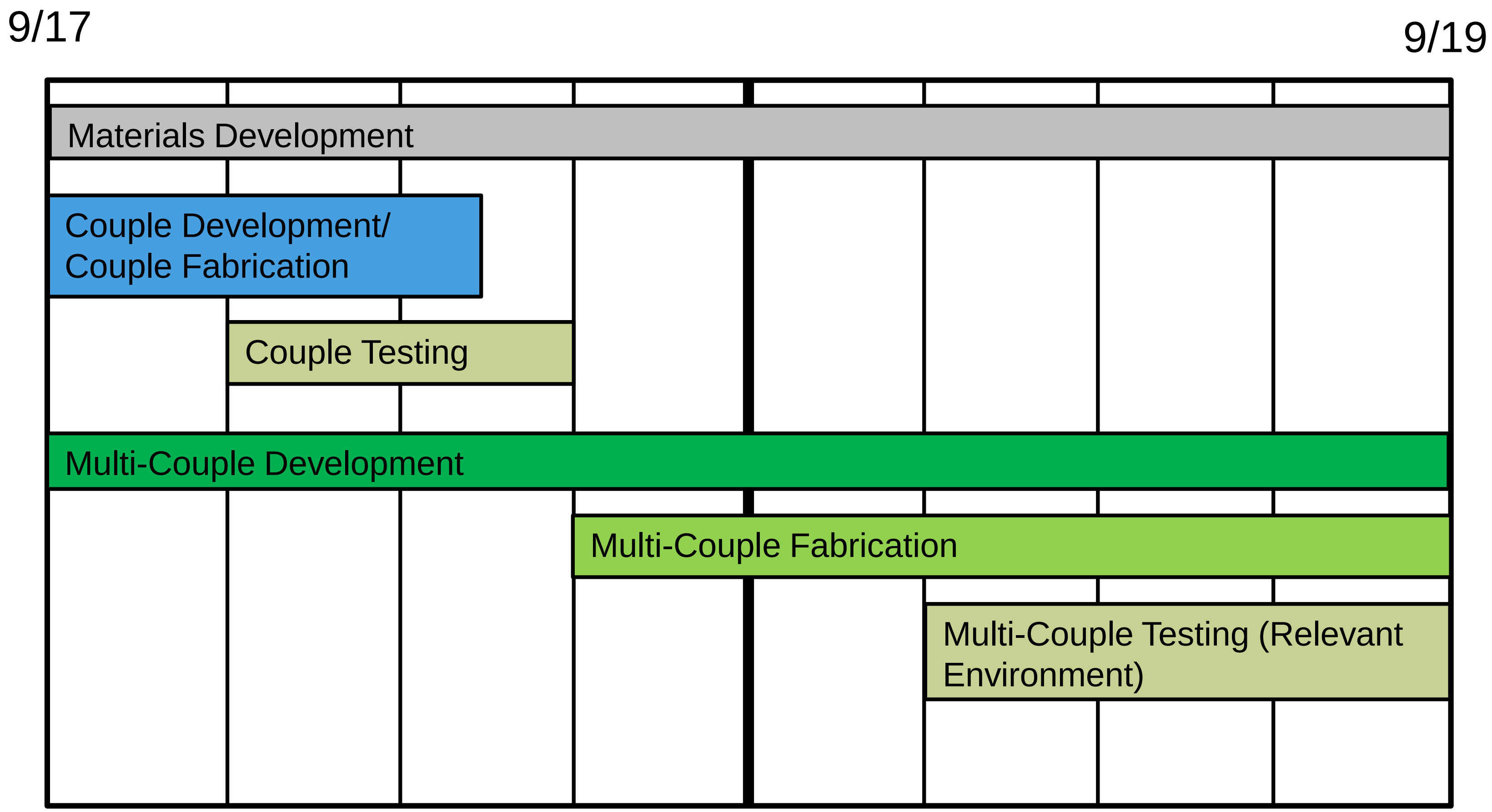


Long Life Thermoelectric Device

Overlap Between Tasks ensures concurrent development



Two Year Development Plan



- Initial Couple Development and Couple Fabrication Allow us to Assess Fabrication Feasibility and Fabrication Process.
- Materials Development – Continuous Activity to End of 9/19.
- Multi-Couple Development Continuous Activity to End of 9/19.
- Multi-Couple Testing – Testing Will Be in Relevant Environment.

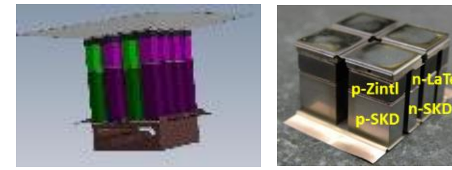
Technology Developed By End of 9/19

	Performance/Function	Fidelity of Analysis	Fidelity of Build	Level of Integration	Environment verification
Materials	TE property life testing Completed		Scale-up sintering developed and documented		Extended test data on high temperature physical, chemical and mechanical properties documented
Elements	TE element processing conditions (sintering, dicing) developed and documented	Element design and performance prediction based on medium fidelity device build	Completed development of TE element interfaces (metallizations, compliant interfaces) necessary for medium fidelity device build	Selection of device-level thermal insulation complete; Completed development of hot side/cold side interface elements	Documented extended test performance under relevant conditions for elements (TE materials, interfaces, sublimation control, dielectrics, insulation)
Devices	Initial development of device assembly procedures for medium fidelity RTG-configured TE devices with prototypic hot/cold shoes	BOL Performance prediction based on TE properties and contact resistances in relevant environment (vacuum or inert gas); Degradation mechanisms quantified	Medium Fidelity TE Device design and configuration	Single device with prototypic thermal insulation and sublimation suppression control	Documented extended performance of low fidelity devices (>5000 hours)
Converters		Updated Life Performance Prediction based on TE elements data, conceptual design and heritage system metrics			Target system conceptual design defined and operating environment updated

Segmented Thermoelectric Device Technology: Remaining Challenges for Achieving Low Power Degradation Rates

Alternate interconnect material(s) - JPL

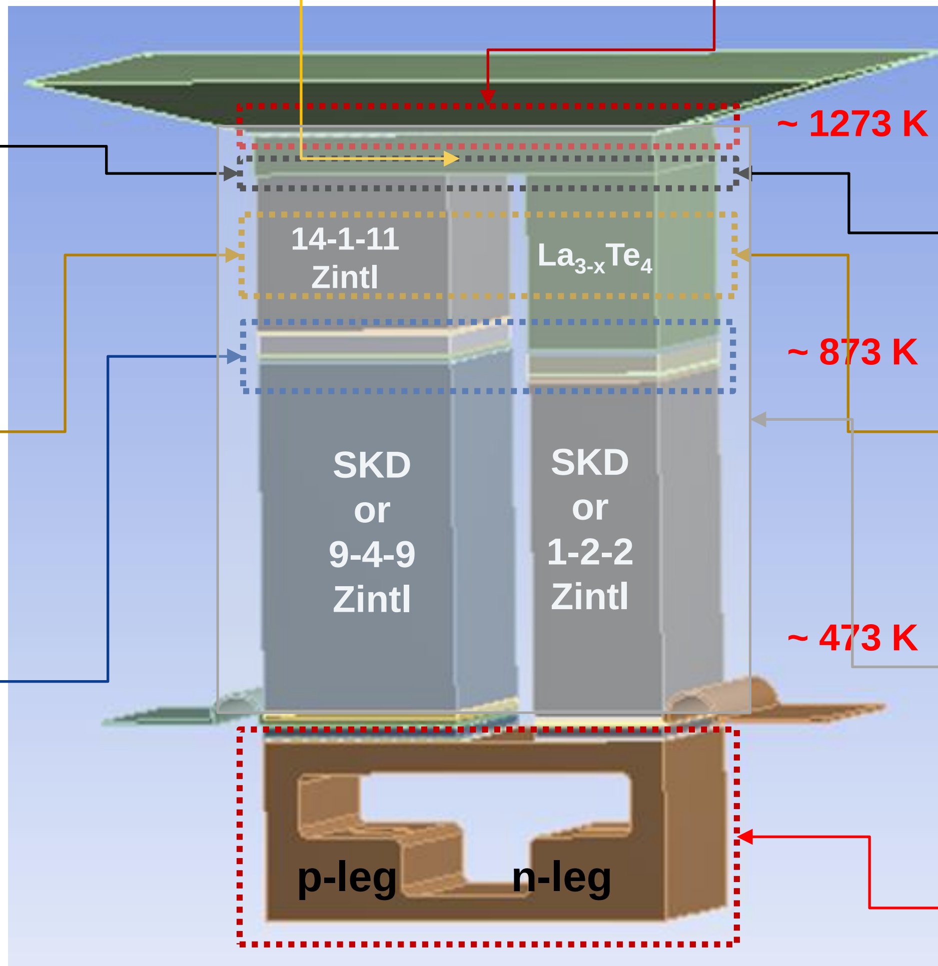
Hot shoe with dielectric layer (modules)



ATEC Segmented Module Technology Advancement

Mechanically robust & chemically stable, hot side interface for 14-1-11 Zintl and composites – **JPL/PSU**

Mechanically robust hot side interface for $La_{3-x}Te_4$ and composites – **JPL/PSU**



Strengthening and stable TE properties for 14-1-11 Zintl and composites - **JPL**

Strengthening and stable TE properties for $La_{3-x}Te_4$ composites - **JPL**

Mechanically compliant, high electrical/thermal conduction segment interfaces - **JPL**

Aerogel thermal insulation / sublimation suppression - **GRC**

Cold shoe with dielectric layer (cantilevered devices, modules)

Development needed

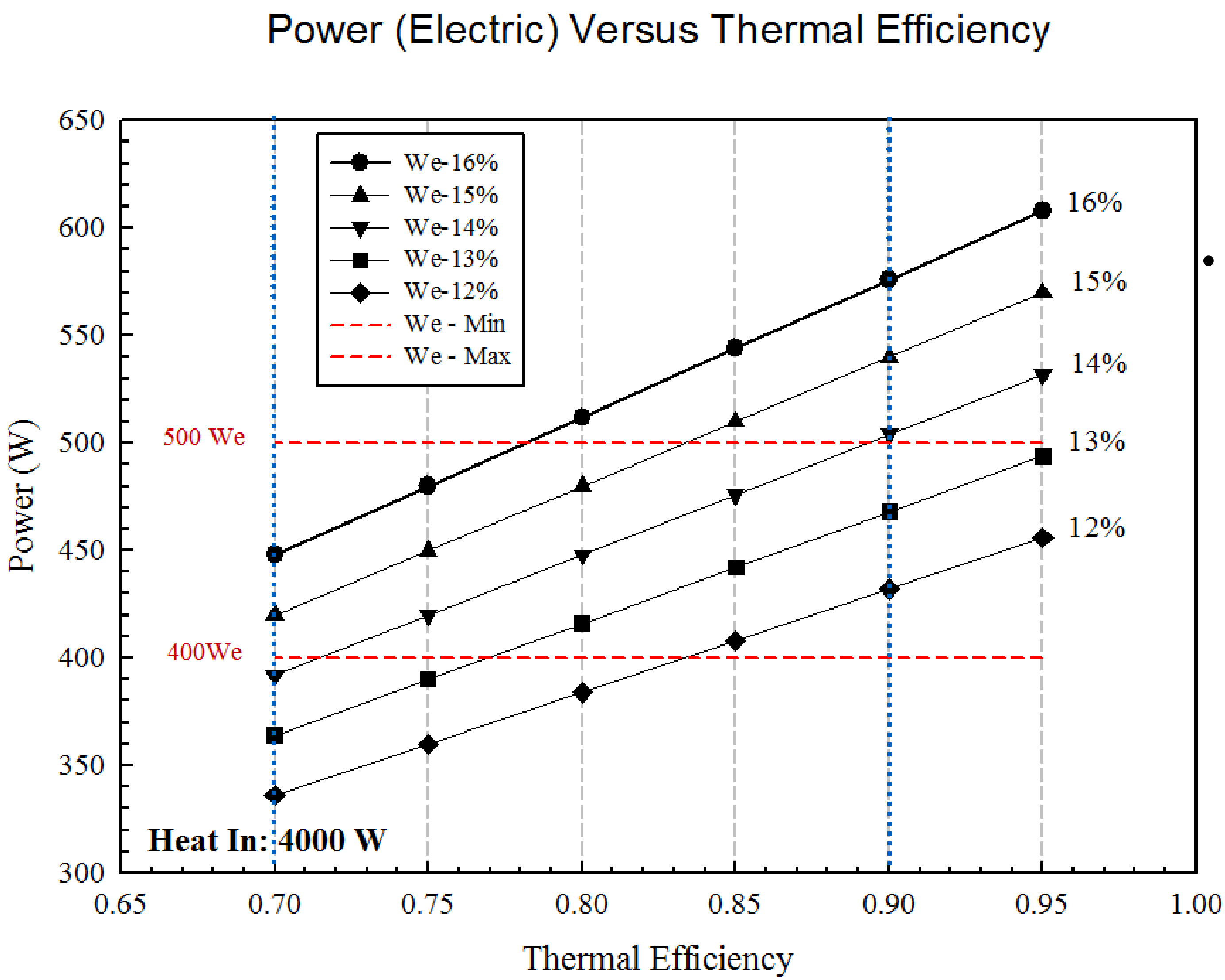
In progress

Couple Configurations For Next Generation RTG

Configuration	n		p		~Couple Efficiency at T_{cj} = 450K	~ Generator Efficiency (16 GPHSs)
	Low	High	Low	High		
1	**1-2-2 Zintl**	**$La_{3-x}Te_4$/composite**	**9-4-9 Zintl**	**14-1-11 Zintl**	**16.6**	**14.8**
2	1-2-2 Zintl	$La_{3-x}Te_4$	9-4-9 Zintl	14-1-11 Zintl	15.3	13.6
3	**SKD**	**$La_{3-x}Te_4$/composite**	**SKD**	**14-1-11 Zintl**	**15.7**	**13.9**
4	SKD	$La_{3-x}Te_4$	SKD	14-1-11 Zintl	14.3	12.7
14		**$La_{3-x}Te_4$/composite**		**14-1-11 Zintl**	**13.6**	**12.1**

- **14-Mn-11** – *High Temperature p-leg (Further developed).*
- **14-Mg-11** – *High Temperature p-leg alternative (Less developed but lower sublimation rate compared to 1-Mn-11).*
- **$La_{3-x}Te_4$** Composite – *High Temperature n-leg (Matrix compound further developed – but composite has higher ZT)* .
- **1-2-2** – *Low Temperature n-leg* (CTE matches that of high-temperature component, low sublimation rate)
- **9-4-9** – *Low Temperature p-leg* (CTE matches that of high-temperature component, low sublimation rate)
- **SKD** – *Low Temperature n- and p- legs (Completed development – but low CTE values require engineering solution)*.

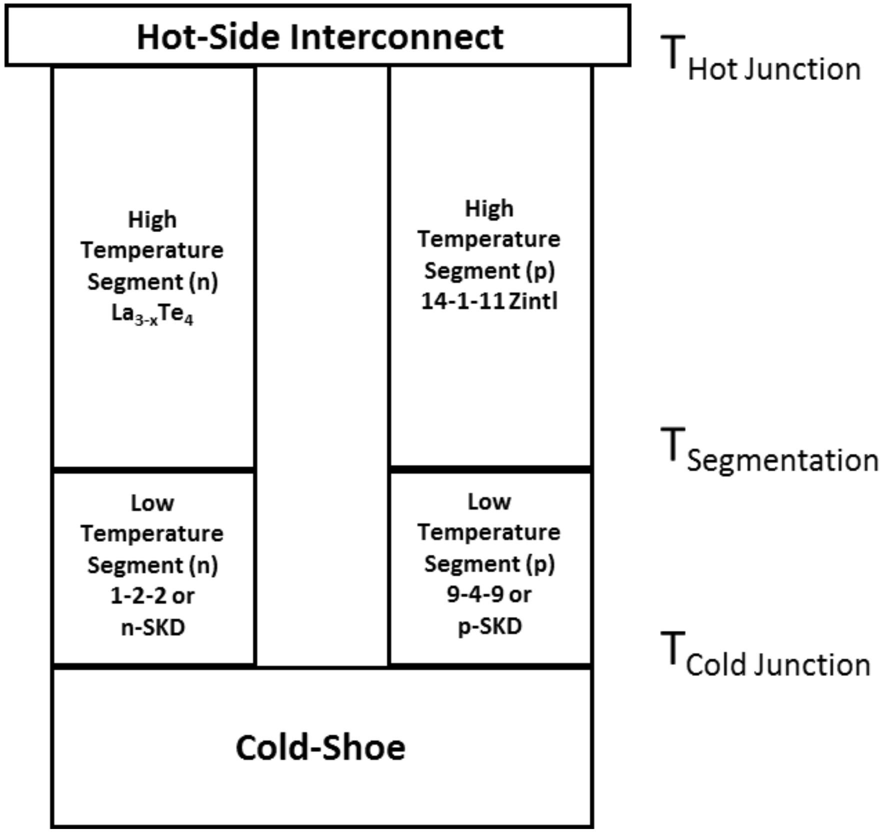
High Efficiency Allows Flexibility



- The higher the couple efficiency, the more “laid-back” we can be with the thermal design.

Or

…We can reduce hot-junction temperature and subsequently improve degradation rate

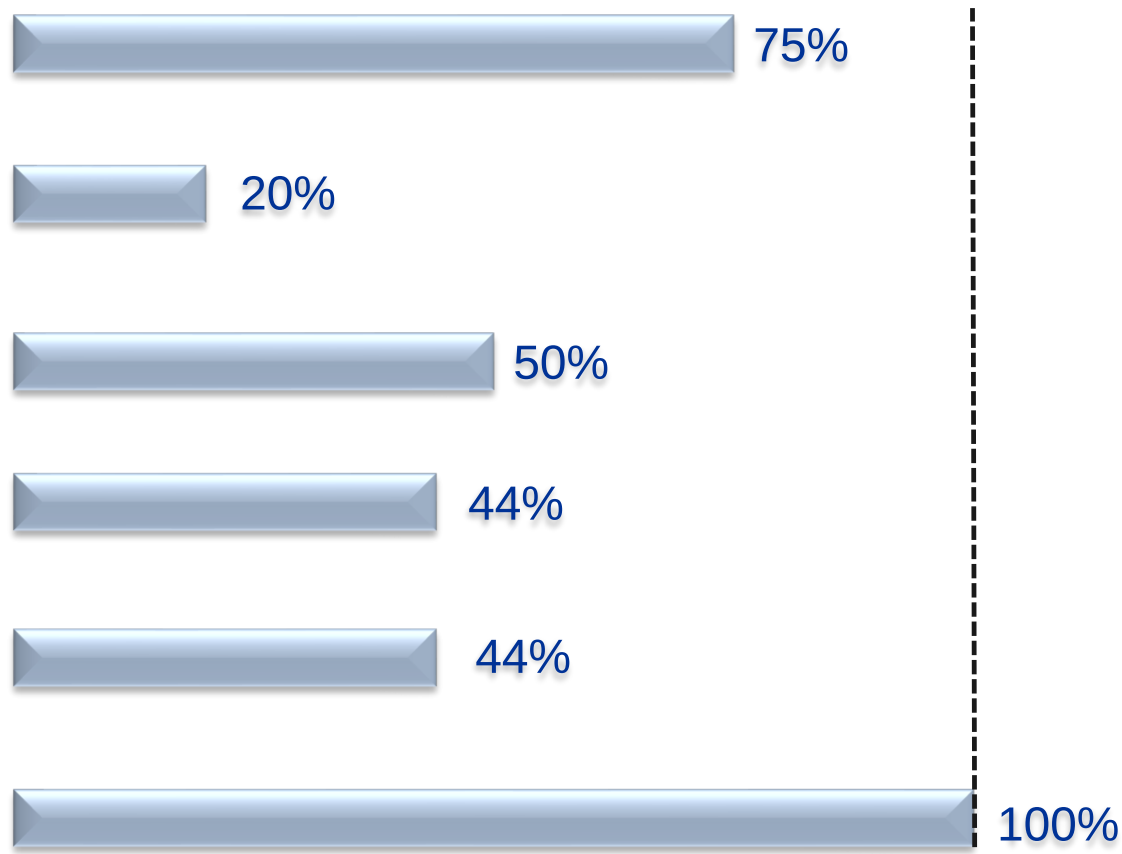


Ex. All Zintl Segmented Couple

T_{HOT} (K)	T_{COLD} (K)	Efficiency (%)
1273.0	450.0	15.80
1223.0	450.0	15.16
1173.0	450.0	14.46
1123.0	450.0	13.73
1073.0	450.0	12.97
1023.0	450.0	12.19
973.0	450.0	11.41

Current Development Status Based on Scorecard

- **14-Mn-11**
- **14-Mg-11**
- **$La_{3-x}Te_4$ Composite**
- **1-2-2**
- **9-4-9**
- **SKD**

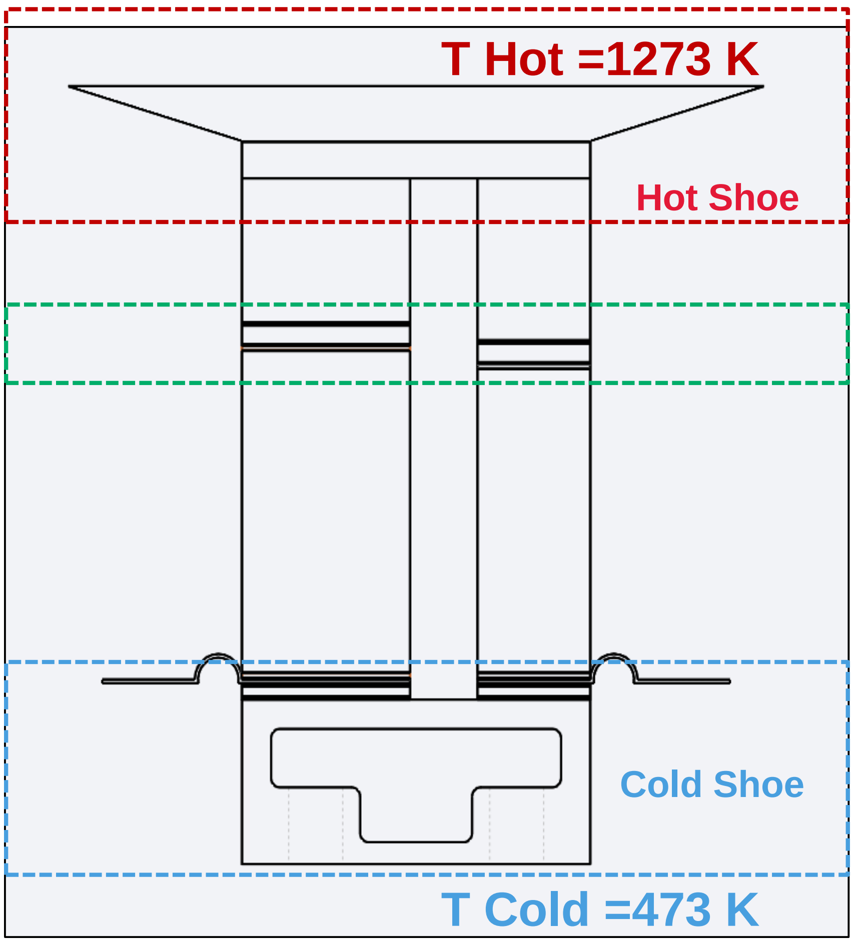


100% Completion before Moving Towards Technology Maturation Phase

"Advanced Thermoelectric Materials For Infusion Into a Potential Next Generation Radioisotope Thermoelectric Generator", Kurt Star, 2/28, 11am, Salon C

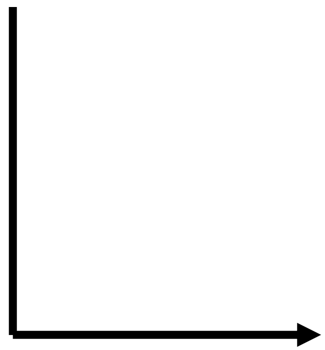
Device Development - Status

❑ Current Focus – Couple Fabrication



Mechanically robust and chemically stable hot-side interfaces for both p- and n- legs.

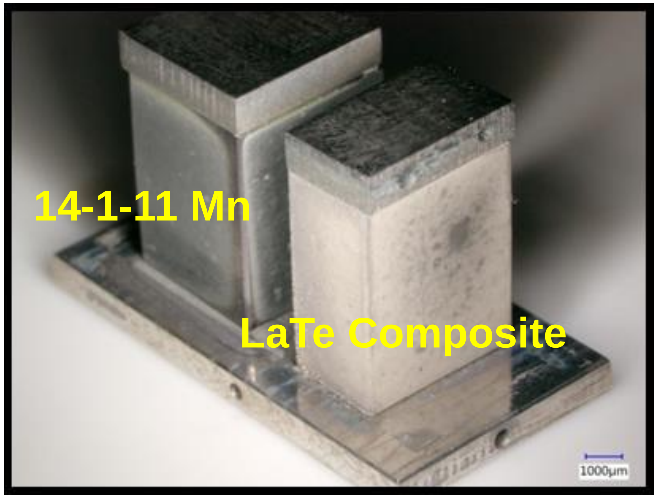
Mechanically compliant, high electrical/thermal conduction segment interfaces.

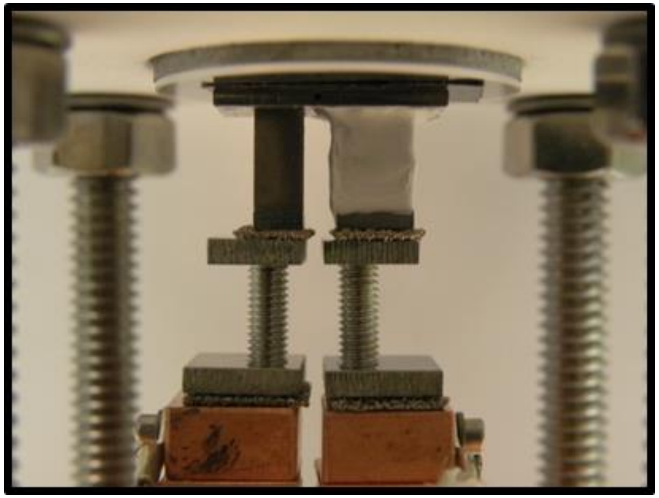


Device Fabrication

Next Generation Configuration 14

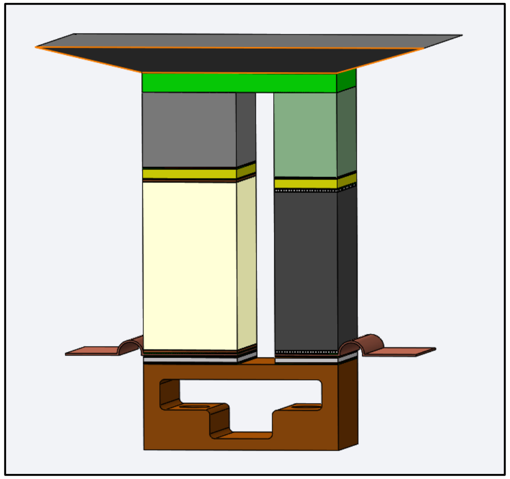
- One of the proof-of-principle high temperature Next Generation RTG couple configurations being developed under TTDP/ATEC (NG-RTG) has demonstrated reasonably stable operation for 3000 hours under nominal hot side temperature of 1275 K

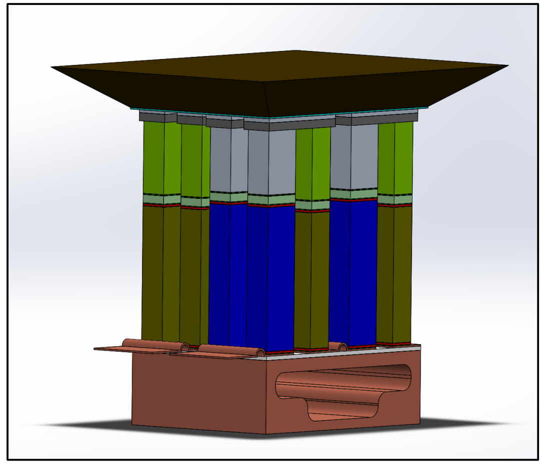


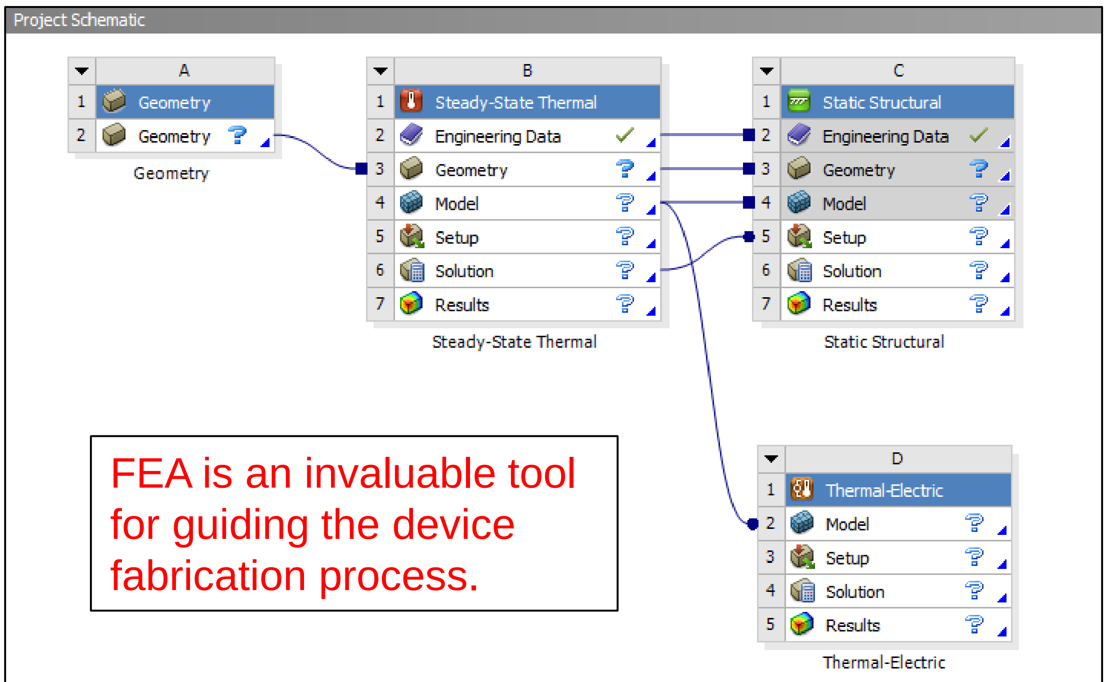


- Couple remained on test for 3000 hours.
- *No sublimation coating was used on the n-leg.*
- Maximum power after 2000 hours at ~95% of BOL.
- Maximum Power after 3000 hours ~ 80% of BOL

FEA – Model Generation



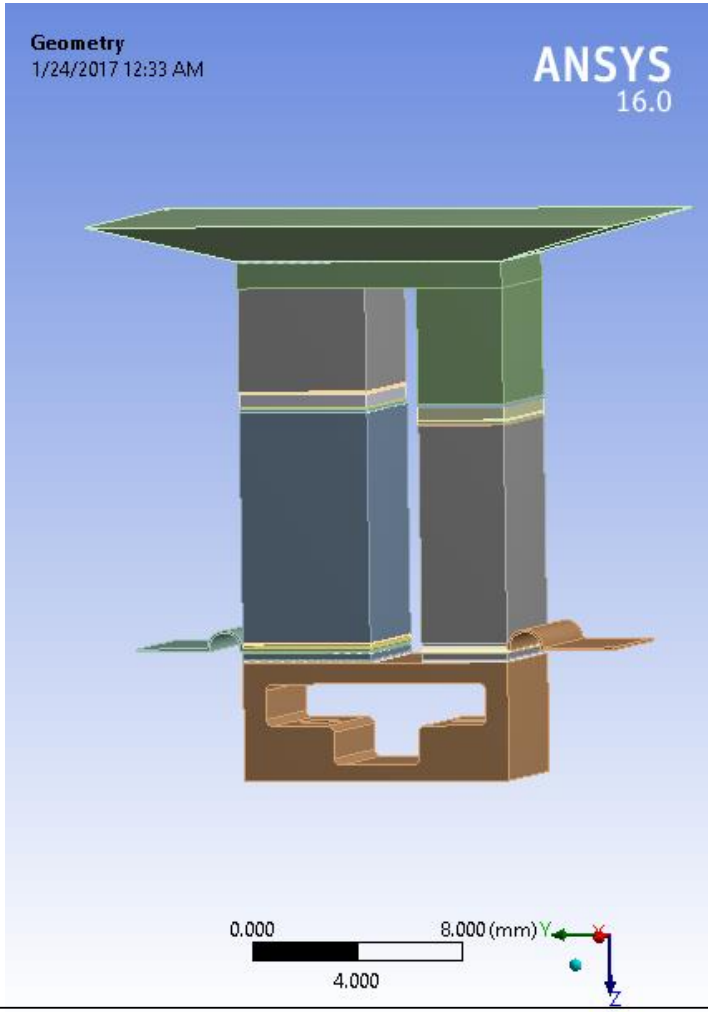


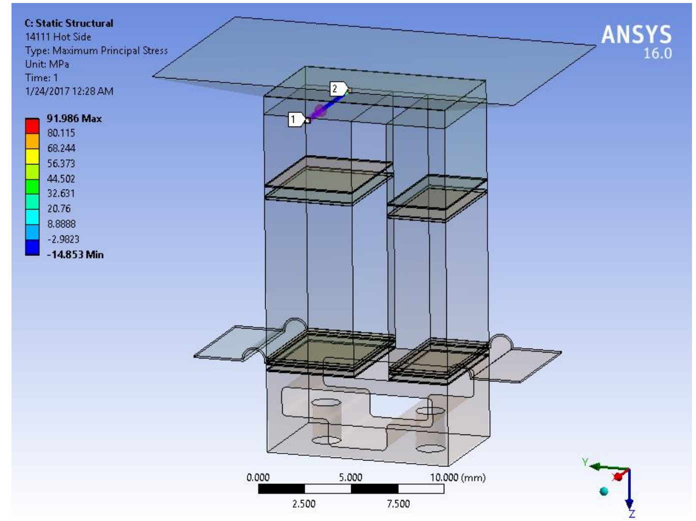


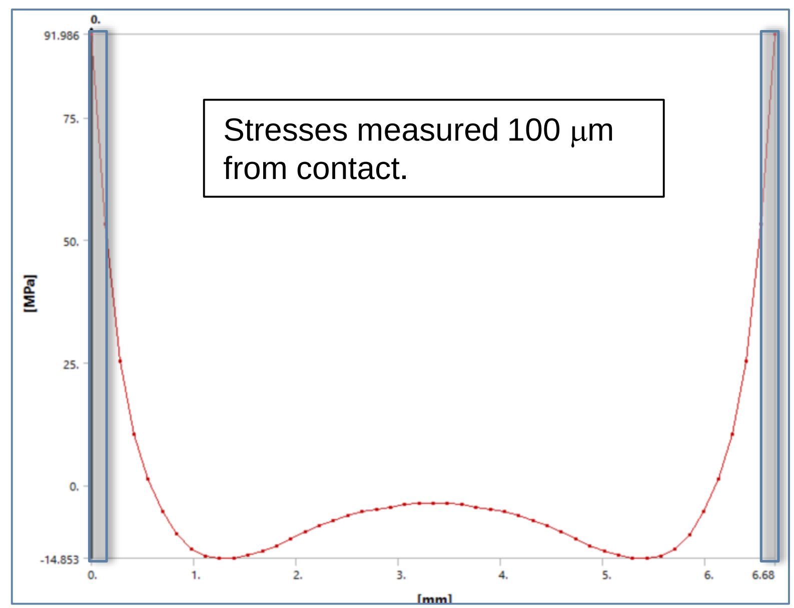
FEA is an invaluable tool for guiding the device fabrication process.

- SolidWorks® is used to generate the models that will be imported into FEA
- Models can be seamlessly imported to ANSYS Workbench® via an associative interface.
- Changes in the SolidWorks® model are automatically updated in ANSYS Workbench®
- We have created an ANSYS Materials database containing mechanical and TE properties for almost all couple module materials.

Segmented Couple – Cantilevered Configuration Thermomechanical Response

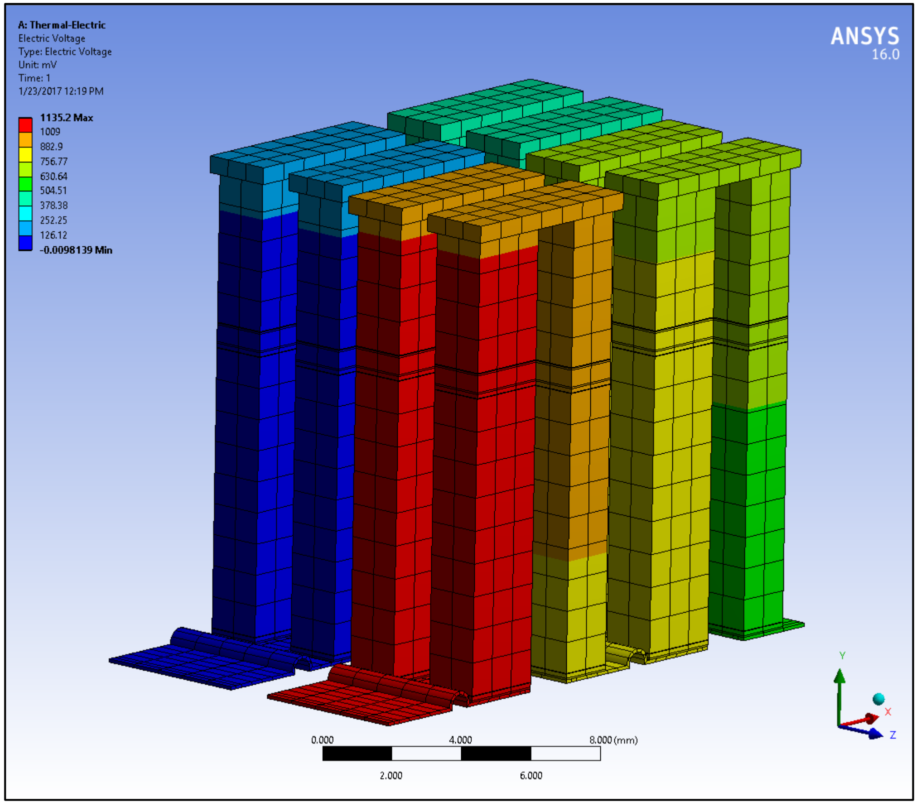


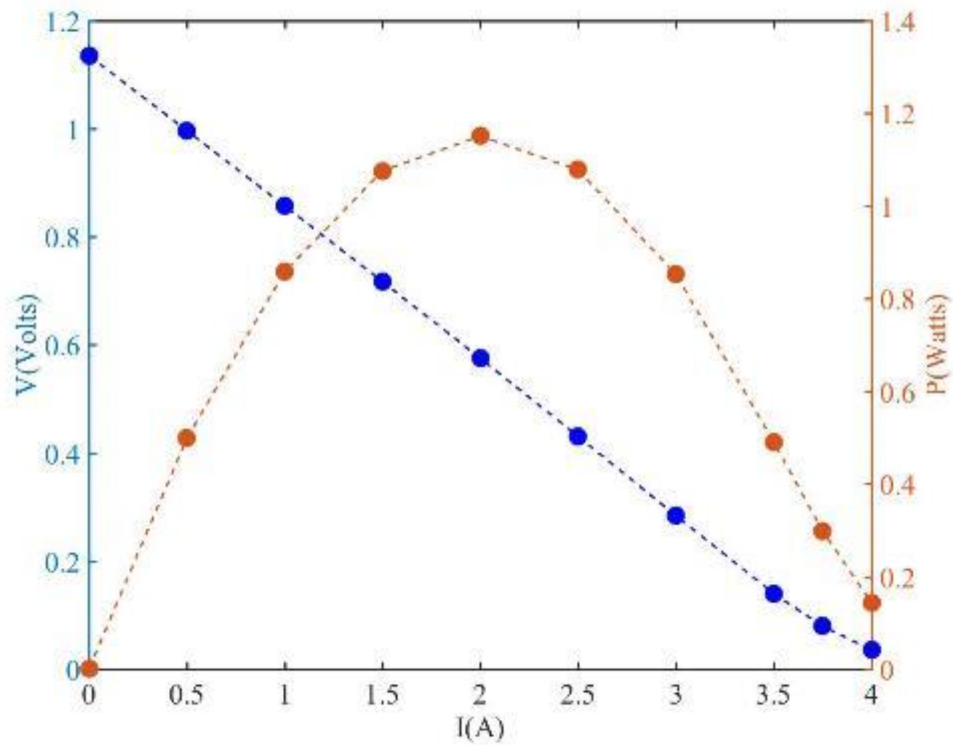




- Analysis to evaluate stress values, and make changes to reduce below UTS (Ultimate Tensile Strength ~ 100 to 200 MPa)

Segmented Couple – Prediction of Thermoelectric Performance





ATEC 8 – couple module, series/parallel configuration: V_{Open} = 1.14 V, I_{Short} =4 A, P_{Max} = 1.15 Watts
FEA allows for concurrent Thermomechanical Analysis and Thermoelectric Analysis – Thermoelectric performance prediction is essential for evaluating measured module performance.

Thot = 1000 C
Tcold= 200 C
Pin =8.6 Watts
Pout = 1.15 Watts
Efficiency = 13.4%

Conclusions

- Materials have been selected for device fabrication.
- Scale-up synthesis has been accomplished for all materials in our materials inventory.
- Considerable progress has been made measuring relevant material properties (TE Properties, Mechanical Properties, Bare Sublimation Rates).
- Developed FEA models for Thermomechanical Analysis and Thermoelectric Analysis.
- Theoretical models are used to understand hot side challenges, in addition to characterization; models are used to aid in hot shoe selection as well.
- Considerable progress has been made in couple testing; evaluating direct bonding process, hot shoe selection.

Acknowledgements

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